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Time trends of daily maximum and minimum temperatures in Catalonia (ne Spain) for the period 1975–2004

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ABSTRACT: Daily maximum and minimum temperatures, T_{max} and T_{min}, and diurnal temperature range, DTR, from 37 temperature stations in Catalonia (NE Spain) are analyzed to detect significant daily time trends for the period 1975–2004. The homogeneity of the series is tested by means of the Standard Normal Homogeneity, the Buishand range and the Pettitt tests. The lack of randomness of the series, suggesting time trends, is also investigated by means of the Von Neumann ratio test. The daily time trends obtained and their spatial and temporal patterns are mainly in agreement with overall time trends recently derived for the Northern Hemisphere. The results indicate generalized increasing annual trends of daily T_{max} and T_{min} (0.5 °C/decade), especially relevant in spring and summer, with values reaching 0.8–0.9 °C/decade, and also remarkable for T_{max} in winter (0.7 °C/decade). In autumn, however, average trends point at a decrease in T_{max} (−0.5 °C/decade). As a result, an average annual decreasing trend of DTR is found, particularly relevant in autumn (−0.9 °C/decade). Several periods with an outstanding number of stations showing significant positive time trends are detected and analyzed during the spring and summer seasons both for daily T_{max} and T_{min}. The only period with a relevant number of significant negative trends is detected in February for daily T_{min}, thus implying a significant increasing trend of DTR during this short winter period. Comparisons are established with large- and regional-scale temperature trends, paying attention to the west Mediterranean atmospheric dynamics change. Copyright © 2009 Royal Meteorological Society

KEY WORDS Global and regional warming; daily T_{max} and T_{min}; DTR; time trends; annual and seasonal scales; homogeneity and randomness tests; NE Spain

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1. Introduction

The effects of global warming on the temperature regimes, mainly due to the increase in the atmospheric greenhouse effect (Trenberth *et al.*, 2007), are widely recognized and many time trend analyses at global, continental, regional and local scales can be cited (Table I). These studies, as many others on temperature trends, have preference for the annual, seasonal and monthly timescales. In this manner, spells of calendar days with significant time trends cannot be detected. The assessment of these daily time trends would be very relevant when future simulations of daily temperature scenarios constrained by the greenhouse gases (GHG) emission would be performed. While at present the simulations mostly operate at seasonal or annual scale (Schubert *et al.*, 1998; McGuffie *et al.*, 1999; Gibelin and Déqué, 2003; Bell *et al.*, 2004; Giorgi *et al.*, 2004; Kjellström, 2004; Räisänen *et al.*, 2004; Sánchez *et al.*, 2004; Ghan and Shippert, 2006), simulations at a shorter time scale are recent and scarce (Meehl and Tebaldi, 2004).

The present study is focused on analyzing daily temperature trends at a small regional scale, Catalonia (NE Spain), along the 1975–2004 recording period. As a reference, according to global climate studies (Trenberth *et al.*, 2007), the global annual temperature rise due to anthropogenic activities for the 1975–2004 period is 0.5 °C, with a smoothed annual value that departs from the monotonic positive increase close to 1984, and it is almost constant close to 1992.

The complex behavior of the atmospheric dynamics makes it difficult and inappropriate to directly transfer the global increase in GHG emission into local or regional temperature regime changes. Then, the schema undertaken is the detailed analysis of time trends affecting calendar day temperatures, instead of annual, seasonal or monthly averaged temperatures, for different locations. Thus, it could be assessed which locations and specific periods of the year are affected by significant temperature trends. Additionally, it could be stated for instance if global warming causes a lengthening of hot summers, relatively warm winters or a smoothing of temperature contrasts between spring and summer and/or summer and autumn. Owing to the daily scale of the analysis, it would be possible to detect what calendar day spells contribute to these patterns.

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Table I. Selected references on temperature time trends at different spatial scales, published in the 1996–2008 period.

Regions	Number of stations	Time period	Trends of	Reference
Globe	5400	1950–1994	Seasonal and annual T_{mean}, T_{max} and T_{min}	Easterling *et al*. (1997)
Globe	∼1000	1856–1998	Seasonal and annual T_{mean}	Jones *et al*. (1999)
Most of the Globe	∼300	1946–1999	Five temperature indices	Frich *et al*. (2002)
Globe	5159	1851–2000	Seasonal and annual T_{mean}	Jones and Moberg (2003)
Globe		1861–1999	Annual T_{mean}	Salinger (2005)
Globe	2223	1951–2003	Seasonal and annual extreme T_{max} and T_{min}, DTR and 11 temperature indices	Alexander *et al*. (2006)
Europe	90	1891–1990	Monthly, seasonal and annual T_{mean}	Schönwiese and Rapp (1997)
United States	361	1900–1996	Annual extreme percentiles of T_{max} and T_{min}	Klein Tank *et al*. (2002)
Europe	199	1946–1999	Daily T_{max}, T_{min} and T_{mean}	Klein Tank *et al*. (2003)
Europe	86	1946–1999	Six indices of daily cold and warm temperature extremes	Klein Tank *et al*. (2003)
Europe	185	1946–1999	Variance and skewness of daily T_{mean}	Klein Tank *et al*. (2005)
Europe	75	1901–2000	Summer and winter percentiles of T_{max} and T_{min}	Moberg *et al*. (2006)
Spain and Canary Islands	11	1901–1989	Seasonal and annual T_{max}, T_{min} and DTR	Oñate and Pou (1996)
Central and southeastern Europe		1951–1990	Seasonal and annual T_{mean}, T_{max}, T_{min} and DTR	Brázdil *et al*. (1996)
NE United States	22	1951–1993	Number of days with T_{max} and T_{min} above and below some thresholds	DeGaetano (1996)
Israel	40	1964–1994	Daily, monthly and annual T_{max}, T_{min}, and DTR	Ben-Gai *et al*., 1999
Venezuela and Colombia	14	1918–1990	Monthly T_{max}, T_{min}, and DTR	Quintana-Gómez (1999)
Canada	210	1900–1998	Daily and seasonal T_{max} and T_{min} 1th,5th,10th,90th,95th and 99th percentiles	Bonsal *et al*. (2001)
New Zealand	22	1951–1998	95th percentile of T_{max}, 5th percentile of T_{min} and four temperature indices	Salinger and Griffiths (2001)
SE Asia and south Pacific	38	1961–1998	Frequency of T_{max} and T_{min} 99th and 1th percentiles	Manton *et al*. (2001)
South Korea	12	1954–1999	Mean seasonal and annual T_{max}, T_{min} and DTR	Jung *et al*. (2002)
China	196	1951–1999	Annual number of hot, frost, warm, cool days, and warm and cool nights	Zhai and Pan (2003)
Iceland	4	1871–2001	Seasonal and annual T_{mean}	Hanna *et al*. (2004)
South Africa	26	1960–2003	Monthly, seasonal and annual T_{mean}, T_{max}, T_{min} and six temperature indices	Kruger and Shongwe (2004)
Poland	51	1951–2000	Monthly T_{mean}	Degirmendžić *et al*. (2004)
Italy	50	1866–1996	Seasonal and annual T_{mean}	Brunetti *et al*. (2004)
Italy	Up to 67	1802–2003	Seasonal and annual T_{mean}, T_{max} and T_{min}	Brunetti *et al*. (2006)
Central and western Europe	81	1901–1999	Seasonal T_{max} and T_{min} 90th and 10th percentiles	Moberg and Jones (2005)
Central and northern South America	48	1961–2003	Annual extreme T_{max} and i_{min}, DTR and six temperature indices	Aguilar *et al*. (2005)

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Table I. (*Continued*).

Regions	Number of stations	Time period	Trends of	Reference
Western Germany	232	1958–2001	Seasonal and annual T_{max} 90th percentile and T_{min} 10th percentile, and two temperature indices	Hundecha and Bárdossy (2005)
Castilla–León (Spain)	171	1961–1997	Monthly, seasonal and annual T_{mean}, T_{max} and T_{min}	Del Río *et al*. (2005, 2007)
Egypt	19	1987–2000	Summer months T_{mean}	Hasanean and Abdel Basset (2006)
Tibetan plateau	66	1961–2003	Daily and monthly T_{max}, T_{min}, and DTR	Liu *et al*. (2006)
South and west Africa	63	1961–2000	Monthly highest and lowest T_{max}, T_{min} and DTR, together to 11 temperature indices	New *et al*. (2006)
Valencia (Spain)	8	1958–2003	Summer months T_{mean}, T_{max}, T_{min}	Miró *et al*. (2006)
California (USA)	331	1950–2000	Annual T_{mean}, T_{max}, T_{min} and DTR	LaDochy *et al*. (2007)
Spain	22	1850–2005	Seasonal and annual T_{mean}, T_{max}, T_{min}	Brunet *et al*. (2007a)
Switzerland	12	1901–2000	Seasonal and annual T_{mean}, T_{max}, T_{min}	Rebetez and Reinhard (2008)
		1975–2004		
Fabra observatory (Spain)	1	1917–1998	Daily T_{max} and T_{min}	Serra *et al*. (2001)
Athens (Greeze)	1	1897–2001	Seasonal and annual T_{max}, T_{min} and DTR	Founda *et al*. (2004)
Hohenheim (Germany)	1	1878–2002	Monthly, seasonal and annual T_{mean}, T_{max}, T_{min} and four temperature indices	Wulfmeyer and Henning-Müller (2006)

Trends of daily maximum and minimum temperature, T_{max} and T_{min}, and daily temperature range (DTR) are evaluated for every station and every calendar day of the year. In spite of the expected complex evolution of every calendar day temperature, linear time trends are a good approach because of the observed smooth annual temperature increase along the analyzed period. For longer term series, due to well known changes in trends, a more suitable technique of fit either by automatic selection of breakpoints and fit of straight lines or by nonlinear models, instead of a simple linear evolution, should have been taken into account (Tomé and Miranda, 2004; Mills, 2006). Trends are determined by two methods. The first is based on a linear regression of the series. This method has some shortcomings when data have an irregular evolution in time, and the trends derived could be then submitted to relevant uncertainties. In this case, the second method, based on the Kendall-tau algorithm, offers more reliable estimations. Trends deduced by both methods are very similar when time irregularities are not very relevant. The statistical significance of every daily time trend is qualitatively investigated for every station by means of the Von Neumann ratio test and quantified by the Mann–Kendall and Kendall–tau tests.

A complementary point of view of the climatic change effects in Catalonia is given by previous analyses on annual precipitation and dry spells, for the years 1950–2000. These analyses have shown how these magnitudes are sensible to the present climatic change. Field significant trends were detected in the number of rainy days for percentiles up to 75, all local trends being negative. Field significant trends were also detected in daily rain intensity, whatever the threshold level, with positive and negative trends. The relevance index indicated an increasing contribution of light and moderate daily episodes to the annual amounts. At the same time, annual rain amounts were characterized by significant local (negative) trends for 2 out of the 39 rain gauges analyzed (Martínez *et al*., 2007) The number of dry spells per year depicted significant trends for the annual and winter-half series, with an overall decreasing trend for 5 and 10 mm/day threshold (Serra *et al*., 2006).

The contents of the manuscript are organized as follows. Section 2 introduces the dataset and several quality controls to detect incoherent data. Different homogeneity tests are applied in Section 3. The results of time trend analysis of daily T_{max}, T_{min} and DTR are presented in Section 4 as follows: first, the average annual trends on daily T_{max}, T_{min} and DTR for every station,

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together with the average annual and seasonal trends for the whole network; second, the spatial average trend for every calendar day; third, histograms depicting the number of stations with significant time trends for every calendar day. From these histograms, it is straightforward to detect a few periods visually (months, weeks and even a few days) for which an outstanding number of stations have positive or negative significant time trends. After that, an average time trend (ATT) is estimated for every relevant time period. A more detailed description is obtained by analyzing the average trends and the number of significant trends for all stations within each period. Comparisons are established with large- and regional-scale temperature trends in Section 5, paying attention to West Mediterranean atmospheric dynamics change and the main conclusions are summarized in Section 6.

2. Data set

The analysis is applied to a series of daily T_{max}, T_{min} and DTR recorded at 37 meteorological stations in Catalonia (NE Spain), pertaining to the *Agencia Estatal de Meteorología* (Ministry of Environment, Spanish Government), with recording period from 1975 to 2004. Fabra Observatory (Reial Acadèmia de Ciències i Arts de Barcelona) is included as station 77. Although temperature series are available since 1950 for many stations, data previous to 1975 have not been considered due to the sharp slope change in temperature records around 1975, well observed from annual global temperature analyses (Trenberth *et al.*, 2007). On the one hand, this sharp change in time trends could mask other lacks of homogeneity, attributable to alterations of station environment and changes of recording devices or data collection procedures, which should be detected by tests of homogeneity. On the other hand, the evaluation of time trends of the temperature regime for the period 1975–2004 would be also masked by considering a longer recording period.

Figure 1a describes the main orographic features of Catalonia. Its regional climate is protected against cold north and northwestern outbreaks by the Pyrenees Range, which may generate the Föhn effect on the north of the country. A long coast of some 400 km facilitates the influence of Mediterranean air masses, especially the summer sea breezes. The Littoral and Pre-Littoral chains diminish this influence, and together with the Pyrenees Range delimit the Central Basin, which remains protected from Mediterranean influences. Figure 1b depicts the locations of the stations. As only stations with a good recording continuity have been considered, the northern part of the domain is not well covered and the spatial distribution is not optimum. It has to be remembered that continuity of the records is highly recommended for right assessments of data homogeneity and accurate evaluation of trends. Figure 1(c) depicts the number of available stations for every recording year. Table II lists station codes, average values and standard deviations of daily T_{max}, T_{min} and DTR for the whole 30-year recording period.

Table II. Expected values of daily T_{max} and T_{min} and DTR ($< T_{max} >$, $< T_{min} >$, $<$ DTR $>$) and their standard deviations (SD_{max}, SD_{min} and SD_{DTR}) for the 37 stations (years 1975–2004).

Code	$< T_{max} >$ (°C)	SD_{max} (°C)	$< T_{min} >$ (°C)	SD_{min} (°C)	$<$ DTR $>$ (°C)	SD_{DTR} (°C)
1	21.1	6.8	12.1	5.6	9.0	3.1
3	20.9	5.9	11.1	6.0	9.8	3.0
4	21.2	6.6	14.7	5.8	6.5	2.4
5	19.3	7.8	8.8	5.7	10.5	4.0
6	20.5	7.5	9.5	6.2	10.9	4.0
7	19.3	7.7	7.7	6.0	11.5	3.7
10	20.5	6.5	10.6	6.3	9.9	3.0
11	21.3	5.8	13.3	5.7	7.9	2.4
12	20.2	5.6	11.4	5.8	8.8	2.3
15	17.6	7.9	6.9	6.3	10.6	3.5
16	16.1	6.6	9.5	6.1	6.7	2.7
17	20.2	6.9	10.3	6.0	9.9	3.0
18	18.6	7.4	6.0	6.4	12.6	4.0
20	21.7	7.1	8.5	6.6	13.2	4.1
21	20.7	7.0	9.4	6.3	11.4	3.7
22	20.9	6.8	8.3	6.5	12.6	3.8
23	18.1	6.1	11.2	5.8	6.9	2.2
25	22.4	8.2	8.8	6.2	13.6	4.9
26	21.0	5.9	10.4	6.3	10.6	3.3
28	19.1	7.0	11.3	6.1	7.8	2.9
29	19.2	7.5	6.0	6.3	13.2	4.6
31	19.8	7.5	7.1	6.1	12.6	4.1
32	19.6	8.3	6.9	6.5	12.7	4.3
34	20.4	6.7	8.5	6.4	11.9	3.8
35	21.4	7.0	8.3	6.5	13.1	4.1
36	19.4	5.5	11.9	5.9	7.5	2.8
42	19.6	8.6	6.9	6.7	12.8	4.3
43	20.5	9.1	7.1	7.0	13.3	4.9
56	19.9	9.5	8.4	6.9	11.4	4.4
59	19.4	8.8	8.3	6.5	11.1	3.8
60	20.1	9.0	7.4	6.8	12.7	4.6
68	20.8	7.9	10.4	5.9	10.5	3.8
69	22.6	8.2	10.5	7.0	12.1	4.3
71	19.7	8.4	10.2	6.5	9.5	3.7
73	22.1	8.5	10.2	6.3	11.3	4.0
75	22.8	6.8	12.3	5.8	10.6	3.4
77	18.9	6.7	11.4	5.6	7.5	2.5

Data quality is checked by several tests applied to the series of daily T_{max} and T_{min}, in agreement with rules proposed by Aguilar *et al.* (2003) and Brunet *et al.* (2007b, 2008). Five different types of quality controls are applied. First, gross errors (T_{max} and T_{min} exceeding unlikely temperatures) are checked. Second, data tolerance is checked by searching for periods longer than a certain number of consecutive days with exactly the same temperatures. Moreover, daily temperature records exceeding a certain number of standard deviations from average values, both quantities computed for every calendar day, have been also considered as not reliable data. Third, a revision of internal consistence is done, verifying that daily T_{max}

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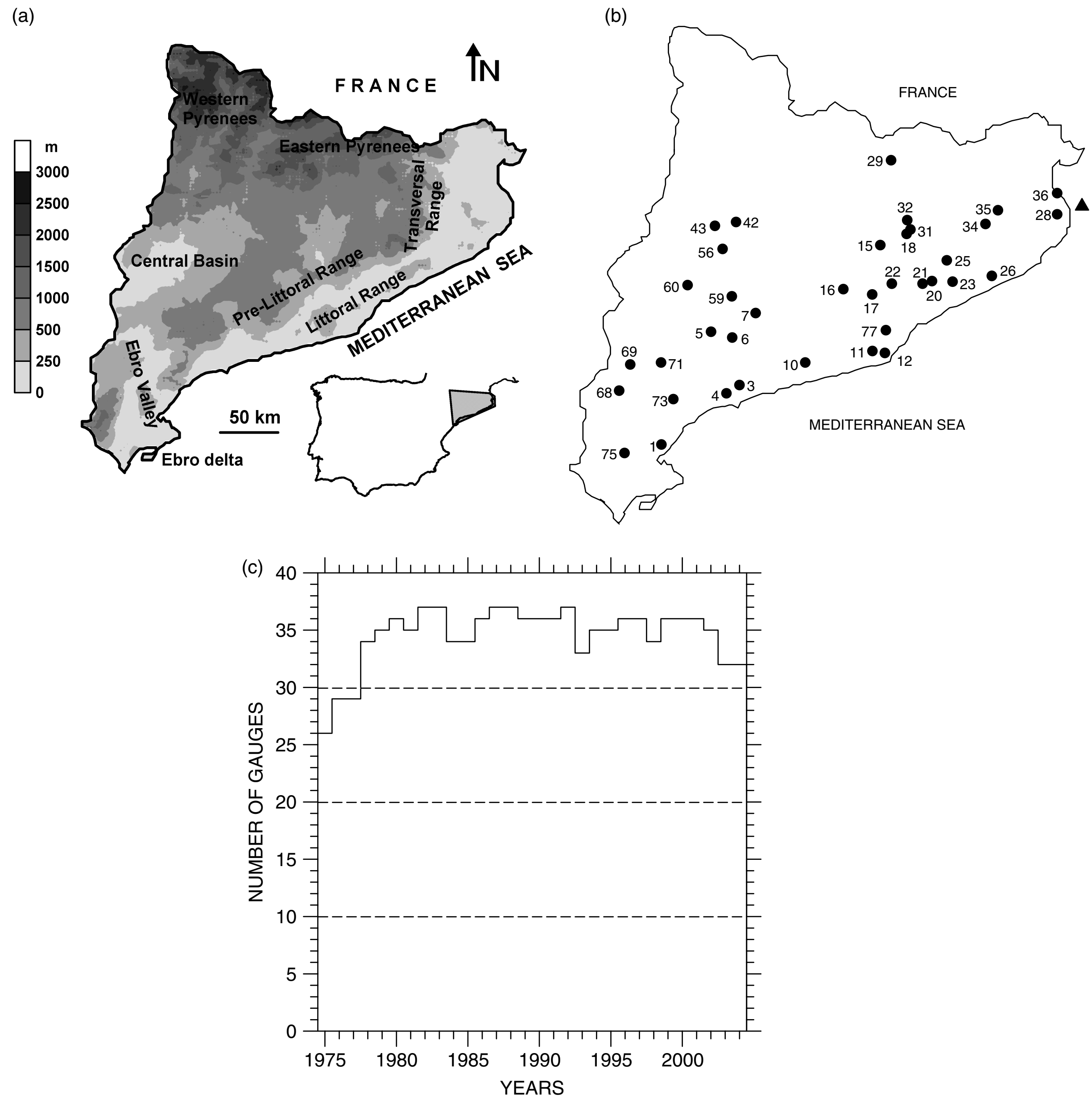

Figure 1. (a) Main orographic features of Catalonia. (b) Location of the 37 stations. L'Estartit station on the Mediterranean continental shelf is indicated by a black triangle. (c) Number of available stations for every year of the recording period.

always exceeds daily T_{min}. Fourth the temporal coherency is tested by checking if consecutive temperature records differ by more than a number of degrees. The last procedure checks the spatial coherency. Differences between a daily temperature record and the average value obtained from the whole network for the same day should not exceed a number of standard deviations, which is also derived from the whole network data.

Daily records exceeding (lowering) 50 (-50)°C are assumed as wrong and more than four consecutive days with the same maximum (minimum) temperature and daily temperatures exceeding thresholds of four standard deviations are considered suspicious of recording errors. Additionally, consecutive records differing by more than 25 °C are discarded. Except for some specific daily records, which have been checked in detail and finally accepted, the rest of incidences on the checking process are assimilated to missing daily data.

Gross errors detected by the first procedure are null. Incidences detected by the internal consistence tests are null for most of the stations; however, for a few temperature series they exceed 0.1% of record lengths. Checking of consecutive daily records with exactly the same temperature indicates a relatively high number of incidences (close to 1% of record lengths) for a few stations, possibly due to poor precision when reading thermometer scales. The other tolerance test depicts a ratio of incidences very close to 0.5% for most of the records. Even though a threshold level of four standard deviations could suggest unlikely records, significant departures from averages along the recording years for a calendar day cannot be discarded. Such departures

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have been also analyzed by means of the Crossing Theory, generating outstanding hot and cold events (Lana *et al.*, in press). With respect to the temporal coherency, consecutive daily records with differences exceeding 25 °C are very unlikely and they can be due to wrong temperature recording or other inappropriate data management. The ratio of incidences does not exceed 0.2%, and sometimes is lower than 0.1%, except for station 69, which is characterized by 2% of daily records not passing this checking process. Finally, the constraint of spatial coherency is accomplished quite well for all series. While most of them present a null ratio of incidences, a few series depict very low ratios from 0.01 to 0.1%. As a summary, 784 327 records have been checked and 8 691 daily incidences detected (1.1% of records).

3. Homogeneity tests and results

Four tests are applied to detect possible departures from homogeneity of temperature series: the standard normal homogeneity test (SNHT) (Alexandersson, 1986; Alexandersson and Moberg, 1997; Tomozeiu *et al.*, 2002; Brunet *et al.*, 2007b; Kyselý and Domonkos, 2006), the Buishand range (Buishand, 1982) and the Pettitt (Pettitt, 1979; Tarhule and Woo, 1998; Gilles *et al.*, 2006; Kyselý and Domonkos, 2006; Kyung-Ja *et al.*, 2006) tests and the Von Neumann ratio test (VNRT) (Von Neumann, 1941; Mitchell *et al.*, 1966; Serra *et al.*, 2001). All of them take as null hypothesis that the elements of the temperature series are independent and identically distributed. For the first three tests, the alternative hypothesis leads to accepting the existence of breaks in the series, thus permitting to detect when these breaks are more likely. The alternative hypothesis for the VNRT establishes a significance percentage for a lack of randomness of the series, which could be a sign of significant time trends. A detailed discussion of these four tests can be found in Wijngaard *et al.* (2003). It is interesting to remark that, whereas the SNHT detects more easily breaks at the beginning and the end of the series, the Buishand range and the Pettitt tests are more sensitive to breaks in the middle. The VNRT assess the randomness of the series, but it is not able to detect breaking points. These four tests are indicated by Aguilar *et al.* (2003) as a valid approach to assess the homogeneity of daily time series. The same authors conclude that homogeneity adjustments of daily data are questionable and they recommend excluding daily data from the analysis when lack of homogeneity is detected. Nevertheless, some controversy exists around this question. For instance, Brunet *et al.* (2008) show a few examples of homogeneity adjustments based on interpolation of monthly adjustment factors on a daily timescale, according to the schema proposed by Vincent *et al.* (2002).

While the SNHT, the Buishand range and the Pettitt tests of homogeneity have been applied to the 37 series of annual average of daily T_{max} and T_{min}, the VNRT has been applied to residuals of monthly average of T_{max} and T_{min}. In this manner, annual and seasonal periodicities are removed for an easier interpretation of departures from the assumption of homogeneity and randomness.

Table III lists the years for which a break is detected in each series by the first three tests. Bold characters indicate the breaking year finally assumed. It is worth mentioning that there is often an agreement in the breaking year detected by the three tests. When two out of three tests detect the same year, this is assumed as the breaking year. There are only a few series for which the three tests indicate different years, the discrepancies being not greater than 2 years.

A very relevant fact is that most of breaks for annual T_{max} and T_{min} are detected for the years 1984–1986 and 1992–1994, which could be linked to two global time trend changes manifested around 1984 and 1992, as mentioned in the Introduction. A natural cause of these common breaking years is the volcanic eruptions of El Chichón, Mexico, in March and April 1982, and Mount Pinatubo, Philippines, in June 1991. Both eruptions reached the stratosphere, injecting high amounts of SO_2 (Robock, 2000; Dunn, 2004), causing a reduction in solar radiation at the surface (decrease in temperatures) and changes in circulation patterns (relative mild winters in the Northern Hemisphere) up to 2 years after the eruption (Parker *et al.*, 1996). Moreover, although breaks caused by changes in observational procedures, instrumentation or station location should not be discarded, it seems very unlikely that such wrong data treatment occurred at the same time for most of the thermometers. The magnitude of the temperature discrepancies at the detected breakpoints is quantified in order to validate or reject the series. The discrepancies evaluated by extrapolation of time trends before and after the breaking year manifest that temperature jumps are not very relevant. However, the homogeneity of the two series (stations 5 and 16) is questionable because of the temperature jumps at their breakpoints. A common breaking year, 1990, is detected by the three tests for annual T_{max} of station 5, with a sharp temperature change of approximately 2.8 °C. For annual T_{min} of station 16, the common breaking year is 1996 and the temperature change is around 1.2 °C. Given that the breaking years are out from the 1984–1986 and 1992–1994 ranges and that temperature jumps are large enough, both series are discarded for the forthcoming analyses. Consequently, 36 daily T_{max} and T_{min} and 35 DTR series out of 37 are considered.

The breaking points of the nondiscarded series have to be attributable to the effects of the two volcanic eruptions in 1982 and 1991. As mentioned earlier, it is unlikely that wrong data management occurs at the same time for most of the thermometers. Additionally, the temperature jumps at the breaking points are quite moderate. In consequence, some lack of homogeneity should be attributable to natural phenomena but not to instrumental or human factors. Then, remembering also the controversy around the homogeneity process at

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Table III. Years for which breaks in the temperature series are detected according to the SNHT and Buishand and Pettitt tests. Bold characters indicate the assumed breaking year. Empty cells correspond to series without significant breaks.

CODE	T_{max}				T_{min}			
	SNHT	BUIS.	PETT.	YEAR	SNHT	BUIS.	PETT.	YEAR
1	1993	1993	1993	**1993**	1993	1986	1986	**1986**
3	1986	1987	1993	**1986**	1986	1986	1986	**1986**
4	1993	1993	1993	**1993**	2002			
5	1990	1990	1990	**1990**	1993	1993	1993	**1993**
6	1993	1993	1993	**1993**	1986	1993	1993	**1993**
7	1986	1986	1986	**1986**	1988	1988	1988	**1988**
10	1996	1993	1993	**1993**	1999	1994	1994	**1994**
11	1993	1993	1993	**1993**	1986	1987	1993	**1986**
12					1993	1993	1993	**1993**
15					1988	1988	1988	**1988**
16	1981	1985	1985	**1985**	1996	1996	1996	**1996**
17	1993	1993	1993	**1993**	1993	1993	1993	**1993**
18	1993	1993	1993	**1993**	1986	1986	1986	**1986**
20	1994	1994	1994	**1994**	1993	1993	1993	**1993**
21	1993	1993	1993	**1993**	1986	1986	1986	**1986**
22	1980	1993	1993	**1993**	1985	1986	1986	**1986**
23					1986	1986	1988	**1986**
25					1980			
26					1986	1986	1986	**1986**
28	1984	1984	1984	**1984**	1979	1990	1994	
29	1980	1982	1982	**1982**				
31	1980	1984	1984	**1984**	1985	1985	1986	**1985**
32	1986	1987	1986	**1986**	1979			
34	1993	1993	1993	**1993**	1981	1985	1985	**1985**
35	1980	1984	1984	**1984**	1986	1986	1987	**1986**
36	1987	1987	1992	**1987**	1980	1985	1987	**1985**
42	1993	1993	1993	**1993**	1983	1983	1983	**1983**
43					1984	1984	1984	**1984**
56					1976	1986	1986	**1986**
59	1982	1983	1986	**1983**	1982	1985	1986	**1986**
60	1992	1992	1992	**1992**	1984	1984	1985	**1984**
68								
69	1993	1993	1993	**1993**				
71	1992	1992	1992	**1992**	1978			
73	1989	1989	1989	**1989**				
75	1993	1993	1993	**1993**	1993	1993	1993	**1993**
77	1993	1993	1993	**1993**	1985	1985	1985	**1985**

daily scale, selected daily series are used for the forthcoming process without any additional treatment. Obviously, natural phenomena and increasing GHG effects could jointly contribute to time trends on T_{max} and T_{min}.

Figure 2 shows some examples of annual average T_{max} and T_{min} (stations 4, 12, 22 and 75). Straight lines depict time trends. For station 4, a sharp increase in T_{max} is observed in 1993 and no relevant change is observed in T_{min}. The reverse situation is observed for station 12. This lack of sharp changes is in agreement with no breaking years detected by the homogeneity tests. Series of station 22 are characterized by smooth decrease (T_{max}) and increase (T_{min}) of the time trends that are coincident with the respective breaking years detected by the tests. Finally, sharp increases are observed for both series of station 75 for the same breaking year, in agreement with that detected by the three homogeneity tests. The increment is remarkable for T_{max} and moderate for T_{min}, and time trends are small.

Figure 3 illustrates the application of the VNRT to the series of monthly residuals of T_{max} and T_{min} of the same stations as Figure 2. It is observed that the empirical statistics (thick and thin solid line respectively) depart from the 95% confidence level bands (dashed lines) around 1980. The nonrandomness of these series has to be accepted then with a probability of at least 95%. It is worth mentioning that the rest of the stations show a similar behavior. Owing to the persistence of the departure of the statistic from the confidence bands, it cannot be discarded that the lack of randomness of the temperature series could be attributable to relevant time trends. This aspect is exhaustively investigated in the next section.

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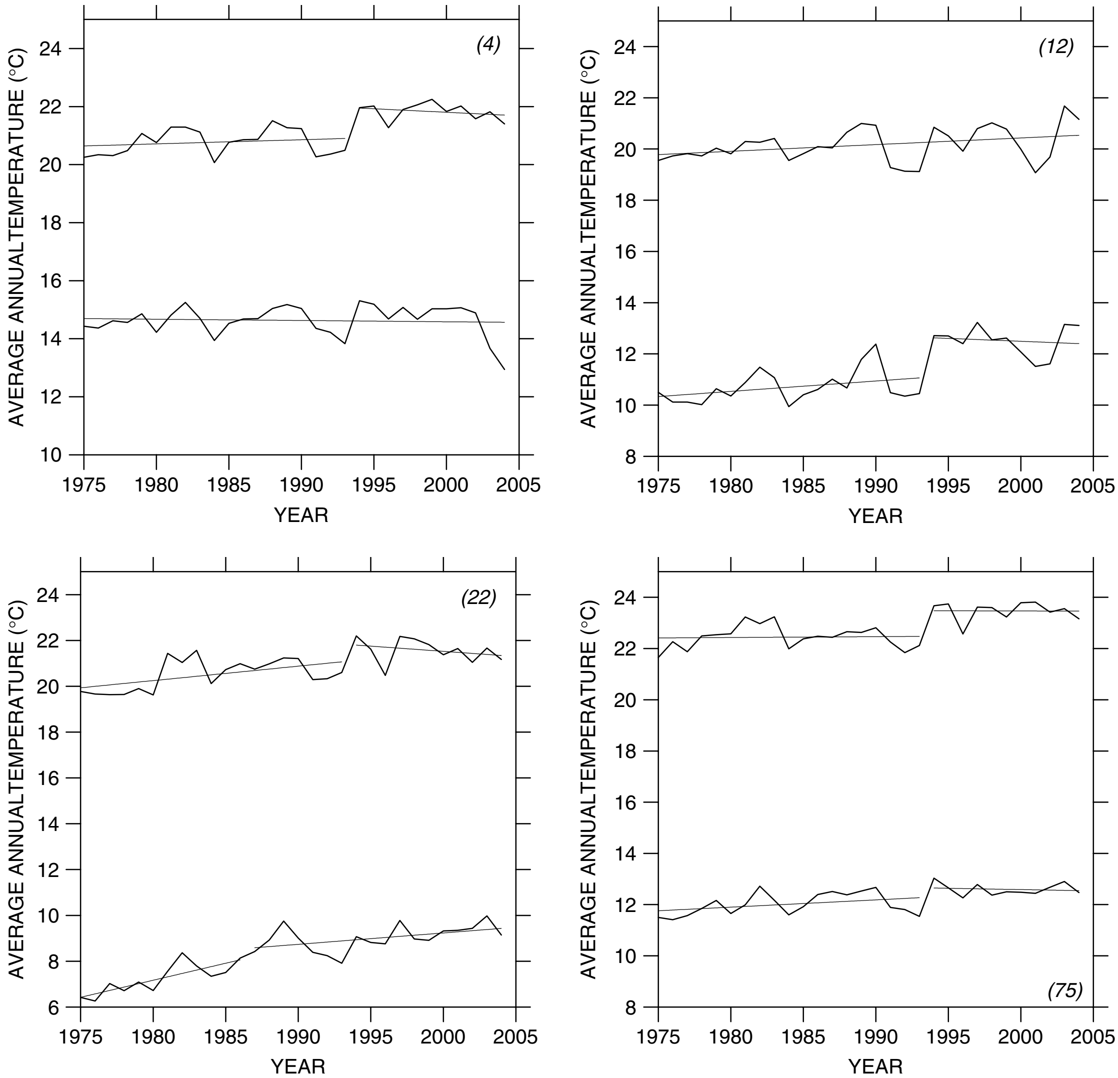

Figure 2. Series of annual average $T_{\max}$ and $T_{\min}$ for stations 4, 12, 22 and 75. Straight lines depict time trends evaluated before and after the breaking years.

4. Temperature time trends

4.1. Methodology

Time trends in $T_{\max}$, $T_{\min}$ and DTR are extensively studied at daily scale. By assuming that, in contrast with volcanic eruptions that could generate short-term effects along a few years, the possible effects on temperatures due to GHG increase are of long-term and continuous nature; however, the estimation of time trends by linear regression might not be a sufficiently robust method. The main reason would be the time irregularity of the series, generated by the superposition of short- and long-continuous components. For all these reasons, the estimation of time trends has been complemented by the most robust Kendall-tau procedure. Owing to the statistical treatment, this procedure favors underlying long-term trends in front of accompanying short-term trends. If a relevant discrepancy exists between both methods, the calendar day trend deduced by the Kendall-tau method is assumed (Sen, 1968; Kunkel *et al.*, 1999; Zhang *et al.*, 2004b). The statistical significance of trends is established by the Mann–Kendall and the Kendall-tau tests (Mitchell, 1966; Sneyers, 1990). Only statistically significant trends, at least at a 95% level, according to both tests are considered for the forthcoming analyses. It is worth mentioning that for most of the stations both tests are in agreement.

The field significance of trends can be validated by a process based on the binomial distribution, using the signs of the local trends, and assuming the lack of field trend as null hypothesis. This assumption would imply that a half of the stations would be associated with positive trends and the other half with negative, with equal probabilities $u = v = 1/2$. If ℓ series out of ℓ_0 are governed by positive (negative) local trends, the corresponding probability, based on the binomial distribution, is

$$P(\ell \leq \ell_0) = \sum_{j=0}^{\ell} \frac{\ell_0\,!}{j!(\ell_0 - j)!} u^j v^{\ell_0 - j} \tag{1}$$

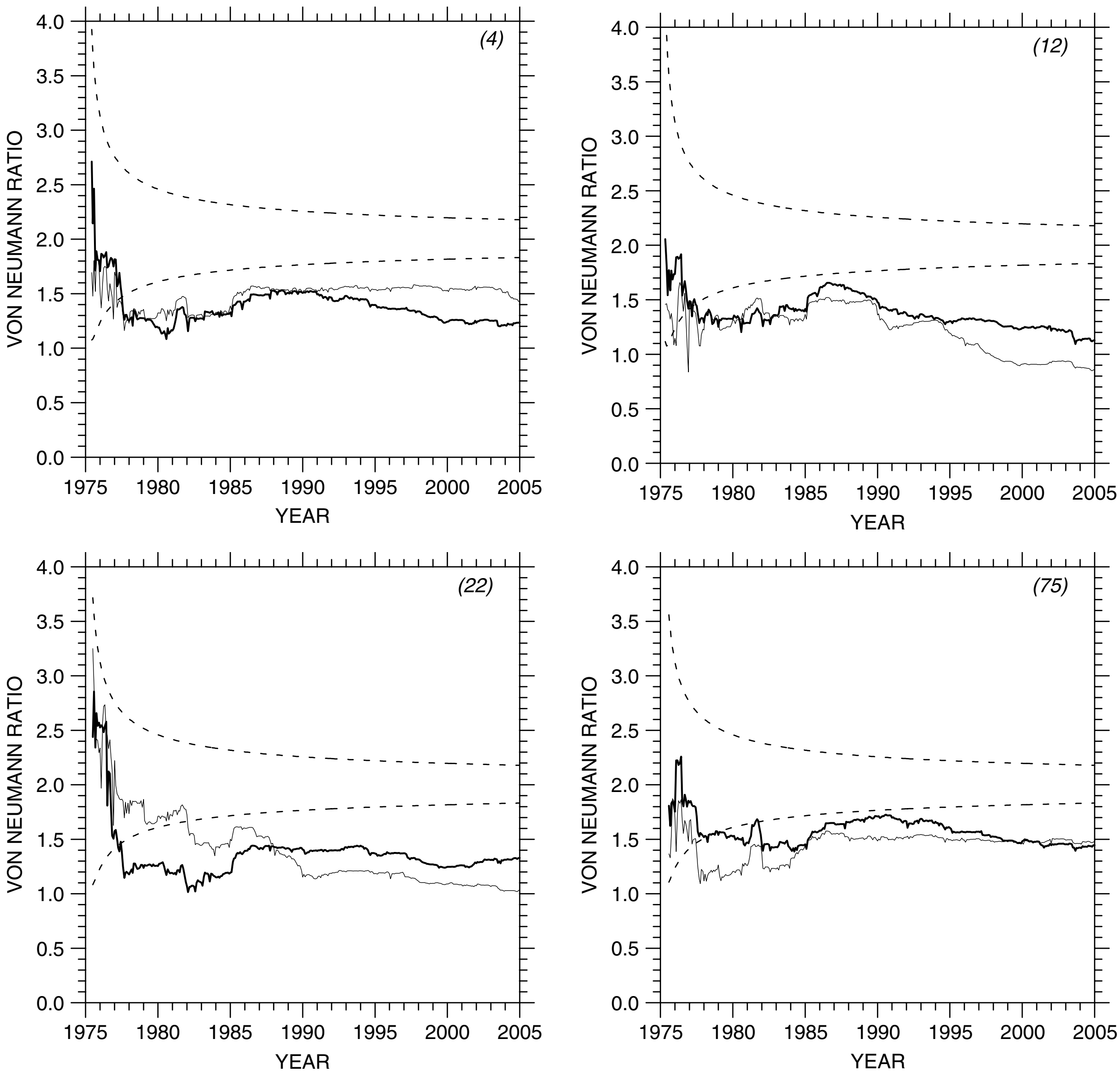

Figure 3. Examples of the VNRT applied to monthly residuals of T_{max} (thick line) and T_{min} (thin line) for the same stations as Figure 2. Dashed lines represent 95% confidence bands.

Similar to the criteria used in the Mann–Kendall and Kendall-tau tests, a field trend is assumed to be significant at the 95% level if $1 - P(\ell \leq \ell_0)$ equals or exceeds 0.95.

4.2. Significant trends of T_{max}, T_{min} and DTR

Figure 4 offers a spatial description of temperature time trends. The annual trend for every station, in degrees centigrade per decade, is estimated as an average of all statistically significant calendar day trends. Table IV lists the number of calendar days with significant positive or negative trends of T_{max}, T_{min} and DTR for every station. Stations can be classified in three ranges (<49, 50–99 and >100) of calendar days with significant trends. For T_{max}, 12 stations belong to the first range, 18 to the second and just three have 100, 103 and 128 days with significant trend. For T_{min}, the classification is similar to that of T_{max} (10, 16 and 6 respectively). A single station has an outstanding number of 156 days with significant trend (155 positive and 1 negative) along the year. This high number implies a very persistent positive trend for this station. It should be also mentioned that two stations (31 and 32) have a null number of days with significant trend, both for T_{max} and T_{min}. The classification for DTR is also quite similar, with 18, 11 and 4 stations for the three ranges. Two stations with 203 (201 negatives and 2 positives) and 238 (237 negatives and 1 positive) significant trends are also worth mentioning. Very persistent negative trends in DTR are then detected along the year for these stations.

Almost all annual average temperature trends are positive, except for seven (T_{max}) and five (T_{min}) station locations. Positive trends often exceed 1.0 °C/decade, while negative trends are more moderate (mostly up to −1.0 °C/decade). The results point then to a generalized increase in daily T_{max} and T_{min}. This increase is confirmed by the validation of the field significance in terms of the binomial distribution. Twenty-nine out of 36 stations with positive time trends confirm the existence of a

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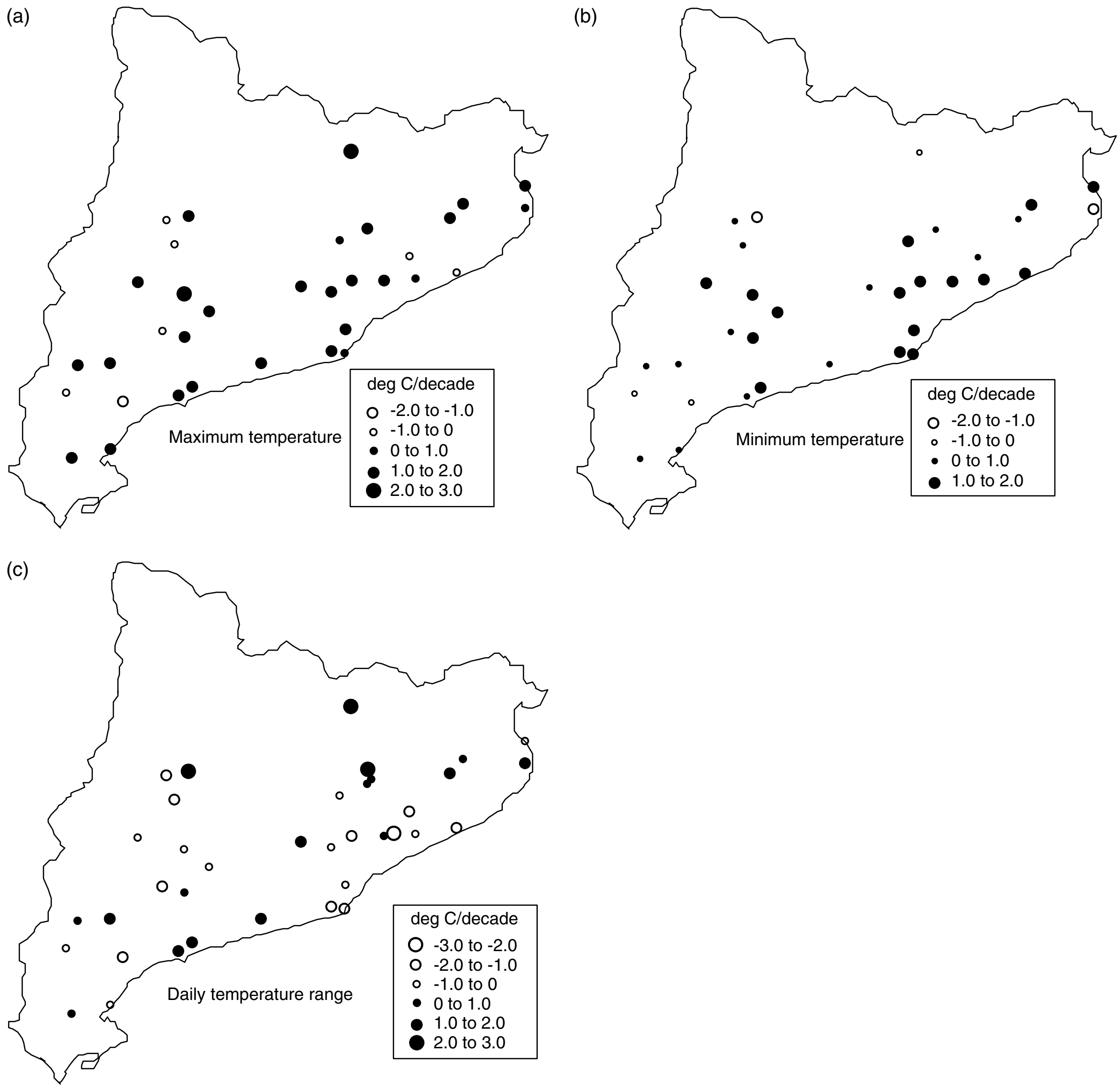

Figure 4. Spatial distribution of the average of significant calendar day trends, in°C/decade, for: (a) T_{max}, (b) T_{min} and (c) DTR.

field positive trend for T_{max} at 99.9% significance level. Similarly, 31 out of 36 series depict positive trends for T_{min} and the field significance trend also exceeds 99.9%. For DTR, 16 positive and 19 negative annual average trends are obtained, most of values ranging from −1.0 to 1.0 °C/decade. The validation process rejects a field significant trend for DTR, as 19 out of 36 stations represent a field negative trend with 63% significance level.

Figures 5 depict the distribution of average daily time trends along the year. For every calendar day, the average trend is obtained by considering all stations having a significant local trend for that day. A first relevant feature is the clear predominance of days with positive average trend for daily T_{max} and T_{min}. The period from mid-May (T_{max}) or mid-April (T_{min}) to mid-September is characterized by a lack of negative trends, excepting for a short period in July. The most relevant period with predominance of days with negative T_{max} trends is observed from mid-September to mid-October. Many peaks exceeding 2.0 °C/decade appear along the year for T_{max}, more sparsely for T_{min}. Negative temperature trends are in general slightly more moderate, especially for T_{min}, but some outstanding values are also obtained. For DTR, positive and negative trends are almost equally distributed along the first half of the year, while a clear predominance of negative trends is observed for the July–December period. Thus, the generalized increase in daily T_{max} and T_{min}, also suggested by Figures 4, results in a decreasing trend of DTR for the second half of the year. These results are also reflected in Table V, which lists the ATT of T_{max}, T_{min} and DTR at seasonal and annual scales, computed from all significant daily trends. T_{max} and T_{min} are characterized by positive trends at annual scale (0.5 °C/decade) and for most of seasons, especially relevant in spring (0.9 °C/decade for T_{max} and 0.8 °C/decade for T_{min}) and summer (0.8 °C/decade for T_{max} and 0.9 °C/decade for T_{min}). A remarkable positive trend is also obtained for T_{max} in winter (0.7 °C/decade). The only average negative trend is detected in autumn for T_{max} (−0.5 °C/decade). DTR clearly tends to decrease

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Table IV. Number of calendar days with significant positive or negative time trends of T_{max}, T_{min} and DTR for every station.

Code	T_{max}			T_{min}			DTR		
	Positive	Negative	Total	Positive	Negative	Total	Positive	Negative	Total
1	39	11	50	67	9	76	9	73	82
3	82	1	83	52	4	56	17	1	18
4	96	2	98	16	13	29	91	1	92
5	–	–	–	35	12	47	–	–	–
6	98	2	100	67	6	73	26	12	38
7	60	8	68	81	5	86	12	48	60
10	127	1	128	27	25	52	63	3	66
11	55	1	56	155	1	156	0	49	49
12	35	3	38	148	1	149	0	127	127
15	33	13	46	57	5	62	7	58	65
16	68	1	69	–	–	–	–	–	–
17	37	1	38	90	0	90	6	25	31
18	61	2	63	48	10	58	21	15	36
20	0	0	0	0	0	0	1	237	238
21	76	1	77	107	3	110	17	18	35
22	60	4	64	141	2	143	2	37	39
23	25	9	34	58	1	59	3	51	54
25	11	36	47	20	19	39	4	33	37
26	13	66	79	121	5	126	2	201	203
28	21	22	43	0	128	128	88	0	88
29	37	3	40	9	23	32	25	2	27
31	0	0	0	0	0	0	13	6	19
32	0	0	0	0	0	0	32	1	33
34	84	2	86	24	9	33	50	1	51
35	56	4	60	48	5	53	14	17	31
36	70	0	70	83	1	84	8	9	17
42	25	9	34	1	120	121	95	3	98
43	12	37	49	33	12	45	7	83	90
56	10	42	52	59	13	72	10	115	125
59	69	7	76	55	4	59	17	32	49
60	30	3	33	48	5	53	11	34	45
68	20	34	54	15	31	46	11	43	54
69	31	4	35	27	14	41	18	13	31
71	103	0	103	2	14	34	103	1	104
72	3	78	81	13	30	43	7	95	102
75	59	1	60	51	7	58	19	7	26
77	43	1	44	96	0	96	5	16	21

at annual scale (−0.4 °C/decade), in summer (−0.4 °C/decade) and especially in autumn (−0.9 °C/decade), while very slight changes are detected for the rest of seasons.

4.3. Spells with a relevant number of significant time trends

A more detailed description of the distribution of time trends along the year is given by Figure 6, where the number of stations with statistically significant trend of daily T_{max}, T_{min} or DTR for each calendar day is represented in three different plots. It is observed that, for many days in spring and summer, a notable number of stations have positive trends for daily T_{max} and T_{min}, whereas this number is more moderate in winter and autumn. In autumn, most of significant trends of daily T_{max} are negative, thus resulting in an average negative trend, as noted before. The main feature observed for DTR is the clear predominance of stations with negative trends during the summer and autumn seasons. Looking at Figure 6, it is possible to distinguish sets of consecutive calendar days, which are termed *spells* from now on, with a relevant number of stations with significant trends of daily T_{max}, T_{min} or DTR. Table VI details the dates and (ATT) of these spells, including the number of days, NST, surpassing 95% field significance. Two spells of T_{max} have five and six consecutive days with very likely field significances, sometimes exceeding 99.9%. Spells of T_{min}, and especially DTR, have a lower number of days with field significance. Thus, from this point of view, some of the spells detected for T_{max} would be more relevant and with more spatial coverage than those corresponding to T_{min} and DTR.

Figure 7 gives a spatial description of the spells, as they depict, for each station, the ATT and the number of days within the spell with significant trends. Four spells are distinguished for daily T_{max} (Table VI). The

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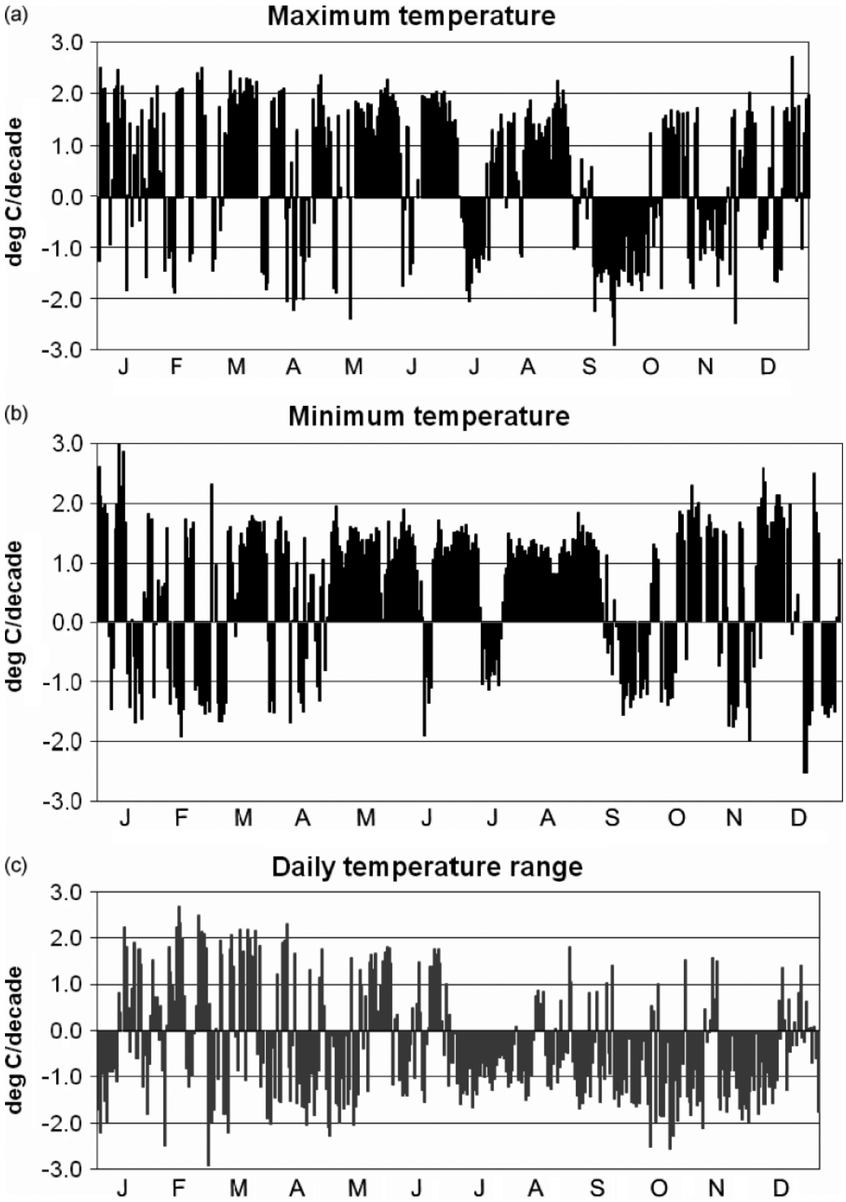

Figure 5. Time trends along the year for: (a) daily T_{max}, (b) daily T_{min} and (c) DTR.

Table V. Average seasonal and annual time trends, in °C/decade, computed considering all significant daily trends for every station.

	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)	Annual
T_{max}	0.69	0.88	0.79	−0.45	0.46
T_{min}	0.09	0.76	0.89	0.30	0.51
DTR	−0.01	−0.04	−0.41	−0.93	−0.36

first two spells (March 12–23 and May 13–June 3), in spring, of 12 and 22 days' duration respectively, are characterized by average trends of 2.12 and 1.88 °C/decade. Figure 7a and 7b shows that, for many stations, the number of days with significant trend is high, and average trends exceed 2.0 °C/decade. The other two spells (June 16–30 and August 9–31), of 15 and 22 days' duration respectively, have average trends of 1.87 and 1.59 °C/decade. Figure 7(c) and (d) shows that the number of days with significant trend is high again for many stations, but average trends exceeding 2.0 °C/decade are sparser than in the previous two spells, especially in the fourth. The relevant increasing trend of daily T_{max}, detected before in spring and summer (Table V), is especially manifested at the start and the end of both seasons according to Figure 6a. For all the spells, the highest trends are mostly reached in nonlittoral sites. Conversely, more moderate values are usually detected in littoral s. The vicinity to the Mediterranean Sea would then smoothen the effects of the global warming in daily T_{max}. The spatial distribution of spell lengths at a different s is, however, heterogeneous and a single pattern cannot be identified.

Five spells are distinguished for daily T_{min} (Table VI). Although the first spell (February 5–11) is quite short (seven days' duration), it is worthy of mention because

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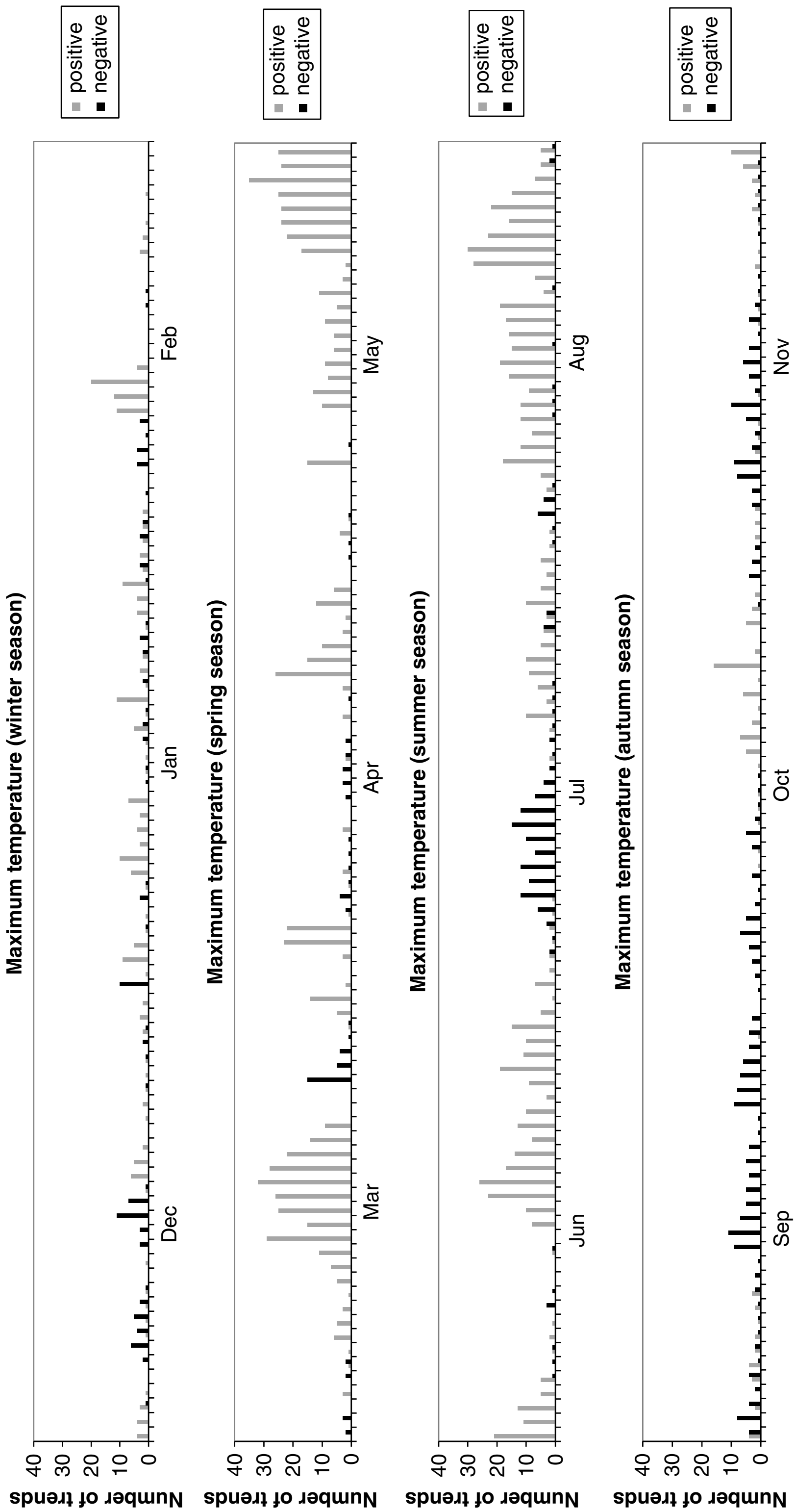

Figure 6. Number of significant time trends for every calendar day for: (a) daily $T_{\max}$, (b) daily $T_{\min}$ and (c) DTR.

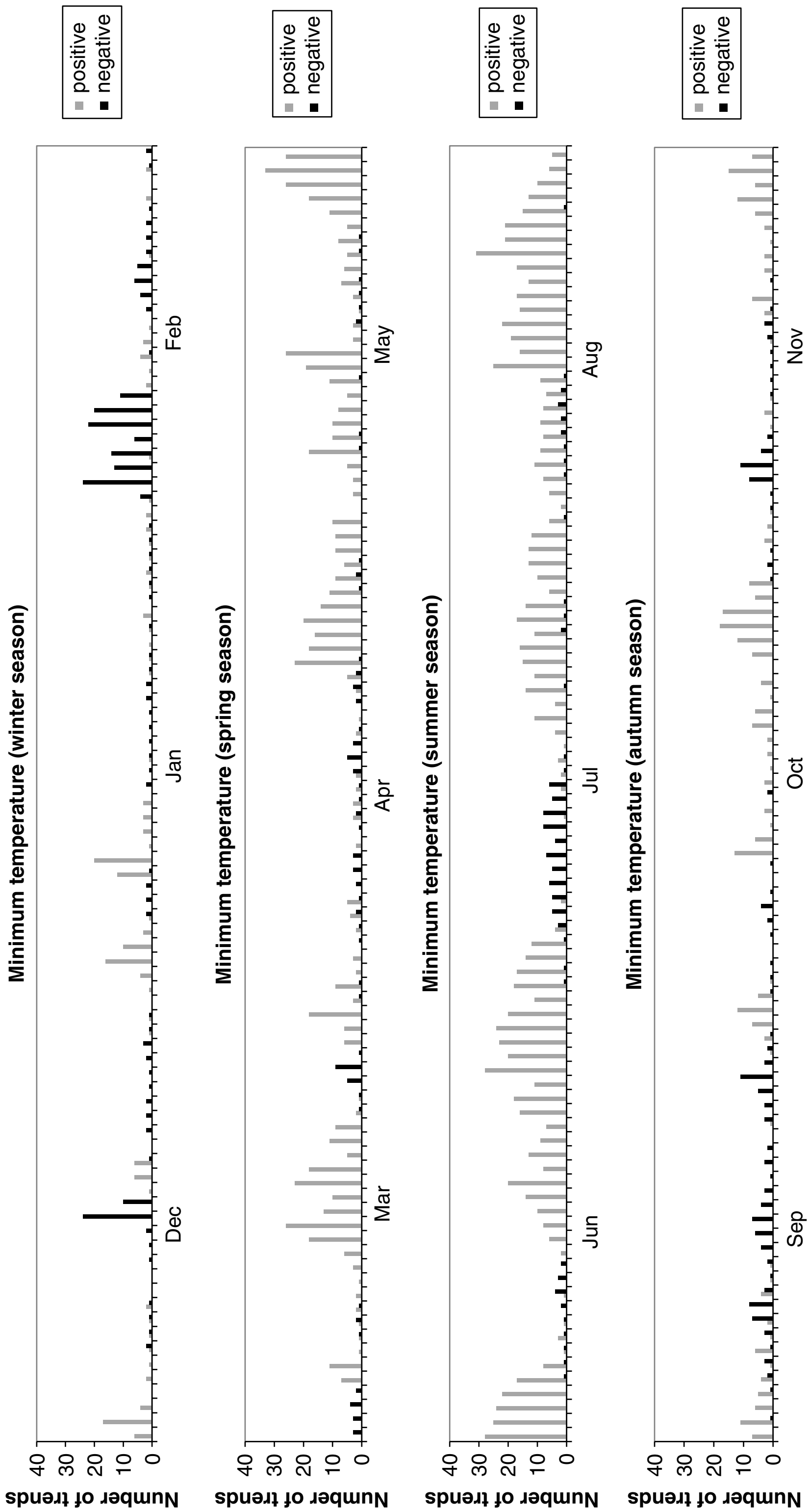

Figure 6. (*Continued*).

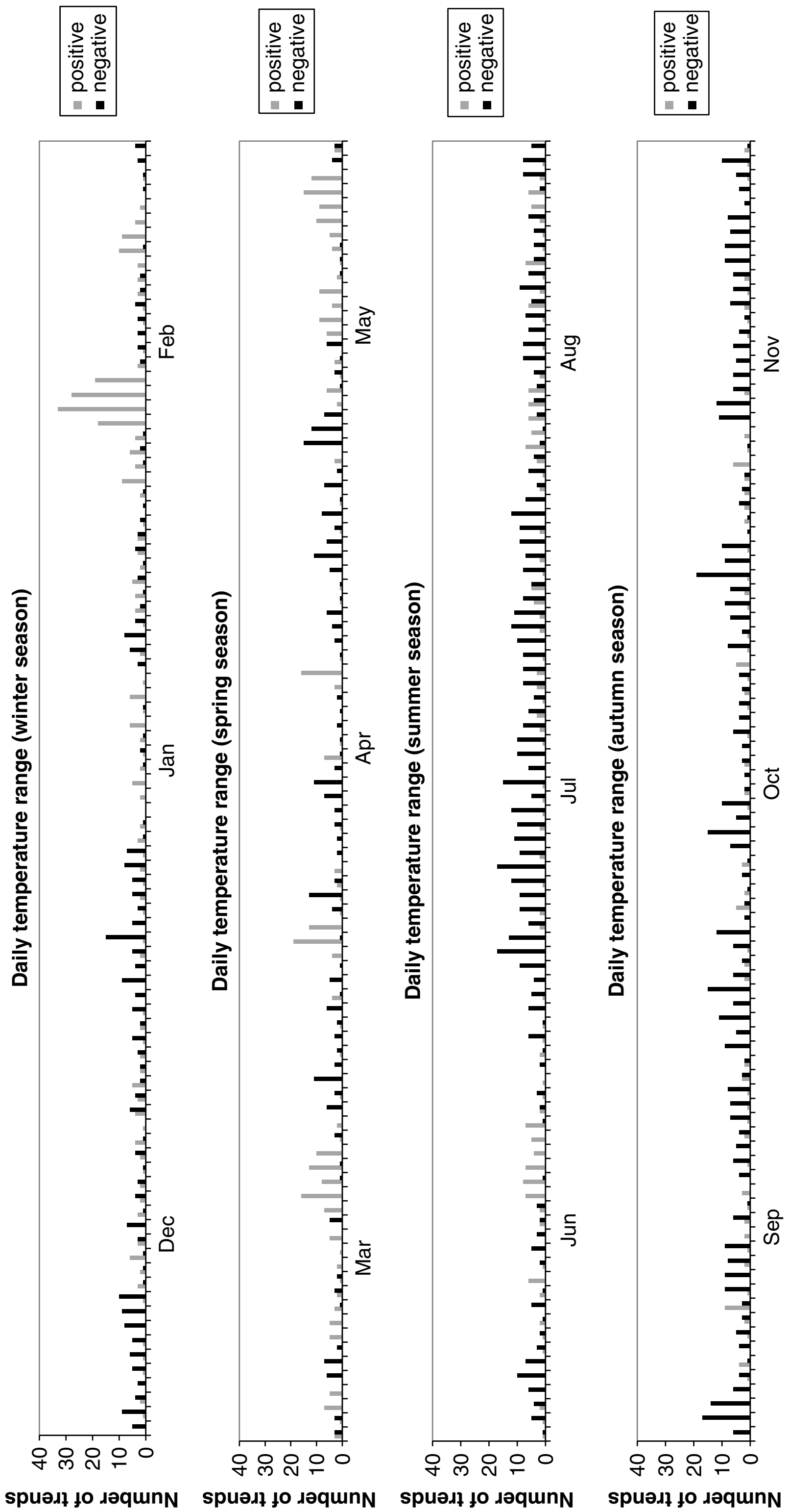

Figure 6. (*Continued*).

Table VI. Spells along the year for which a relevant number of stations have significant daily trends of T_{max}, T_{min} or DTR and their average time trends, ATT, in °C/decade. The number of days with field significant trends, NST, is also indicated for every spell.

T_{max}			T_{min}			DTR		
Dates	ATT	NST	Dates	ATT	NST	Dates	ATT	NST
	–		February 5–11	−1.47	1	February 9–12	2.35	0
March 12–23	2.12	5	March 15–23	1.66	1	–	–	–
May 13–June 3	1.88	6	April 25–June 6	1.38	0	–	–	–
June 16–30	1.87	1	June 15–July 7	1.38	1	–	–	–
August 9–31	1.59	2	July 22–August 31	1.23	2	July 1–August 6	−0.97	2

this is the only spell with negative temperature trends. For most of the stations, the temperature decrease exceeds 1.0 °C/decade (Figure 8a), giving an average trend for the spell of −1.47 °C/decade. The rest of the spells cover almost all spring and summer seasons and are characterized by a clear predominance of positive trends of daily T_{min}, as can be seen in Figure 6b. The average trends are 1.66, 1.38, 1.38 and 1.23 °C/decade respectively (Table VI). The number of days with significant trend and the average trend for each station are shown in Figure 8b, c, d and e, respectively. The second (March 15–23, nine days' duration) and third (April 25 – June 6, 43 days' duration) spells occur in spring and are characterized by average trends exceeding 1.0 °C/decade for almost all of stations, without a clear distinction among littoral or nonlittoral sites. The fourth (June 15–July 7, 23 days' duration) and fifth (July 22 – August 31, 41 days' duration) spells occur in summer, at similar dates as the third and fourth spells of T_{max}. Except for three stations with small negative trends, the rest have positive trends, mostly exceeding 1.0 °C/decade. Distinctions among littoral or nonlittoral sites are not clear either. Thus, vicinity to the Mediterranean Sea does not seem to be a key factor in daily T_{min} trends. The spatial distribution of the spell lengths is very heterogeneous again and, as for daily T_{max}, a single pattern cannot be easily identified.

Two spells are distinguished for DTR. A very short spell (February 9–12, four days' duration), almost overlapped with that of decreasing T_{min}, is identified, thus resulting in an outstanding average positive trend of 2.35 °C/decade (Table V). Most of the stations have significant trends for three or four days, and the highest trends are mainly located in the northeast of Catalonia (Figure 9a). The second spell (July 1–August 6, 37 days' duration) is mainly characterized by negative trends, except for a few sites. No spatial pattern is identified either. The average trend is −0.97 °C/decade.

As a summary, the daily temperature regime of Catalonia manifests very clear signs of increasing trends, especially in spring and summer. Owing to the complex orography of Catalonia, the temperate effects of the Mediterranean Sea and the atmospheric circulation patterns in the region, spatial and temporal patterns of the temperature regime variations are quite complex. From a spatial point of view, only the temperate effect due to the vicinity to the Mediterranean Sea could smoothen partially positive trends of daily T_{max}. The conclusions for the time evolution are more clear and interesting. In agreement with Figure 6(a) and 6(b) and Tables V and VI, in the future, the temperature effects of an incoming climatic change due to global warming would result in hotter springs and summers, especially at the beginning and the end of these seasons. Nevertheless, a few consecutive days within these seasons without relevant trends are also expected. Additionally, a short winter spell would be characterized by an increasing trend on DTR, due to decreasing T_{min} and lack of statistically significant trends for T_{max}.

5. Discussion

5.1. Physical causes

In addition to the rapid increase in GHG (Trenberth *et al.*, 2007), other causes are taking part in the atmospheric warming. Solar forcing on global surface temperature during last century has been analyzed recently (Scafetta and West, 2006a,b). According to these authors, its contribution represents 25–35% of the 1980–2000 global warming. At the same time, the reduction in solar dimming in favor of solar brightening in the 1980s, caused by a reduction in emissions of both scattering sulphate and absorbing black carbon aerosols is of minor order in relation to greenhouse forcing as a cause of global warming (Wild *et al.*, 2007).

According to the investigation of the possible impacts of enhanced GHG and sulphate aerosols on extratropical cyclone activity all over the world about the year 2050, Geng and Sugi (2003) have found that the total cyclone density will decrease significantly in midlatitudes of the Northern Hemisphere during December–January–February (DJF) and June–July–August (JJA) seasons. And although weak and medium-strength cyclones decrease, the density of strong cyclones increases by more than 20% in JJA. The reasons for these changes are linked to the decrease in baroclinicity in the lower troposphere, mainly caused by the decrease in the meridional temperature gradient. Previous studies on cyclones over the North Atlantic by Knippertz *et al.* (2000) pointed also toward a decrease in total cyclone

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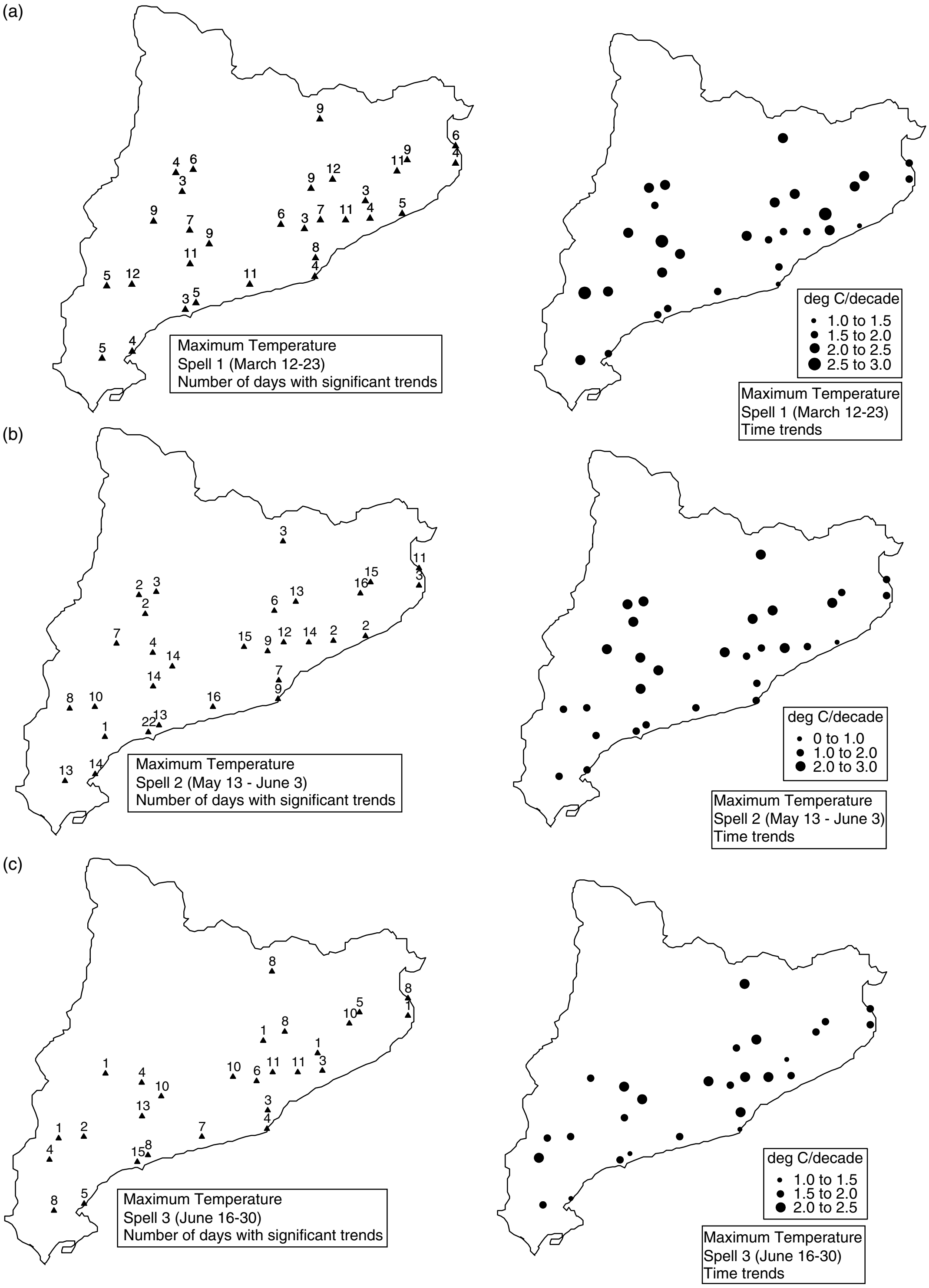

Figure 7. Number of days with significant trends and average weighted trends for the four spells of daily T_{max}.

and an increase in strong cyclones, with a position shift of their tracks poleward and eastward. This shift of the storm tracks has also been found by other authors (Ulbrich and Christoph, 1999; Pinto *et al.*, 2007). This behavior is consistent with the 1948–2002 arctic cyclone activity (60°–90°N), which shows as the number and intensity of cyclones entering the Arctic from the mid-latitudes has increased, suggesting a shift of storm tracks toward the Arctic, particularly in summer (McCabe *et al.*, 2001; Zhang *et al*, 2004a). The Mediterranean Basin would also suffer a decrease in the overall cyclonic activity, consistent with observations in the twentieth century (Lionello *et al.*, 2006), and an increase in deep cyclones in a doubled CO_2 climate scenario (Lionello *et al.*, 2002). According to these studies, it is to suppose an increase of southwesterlies in the Iberian Peninsula, at least in winter, along the twenty-first century, with the consequent warming. In case of a year with a winter of positive

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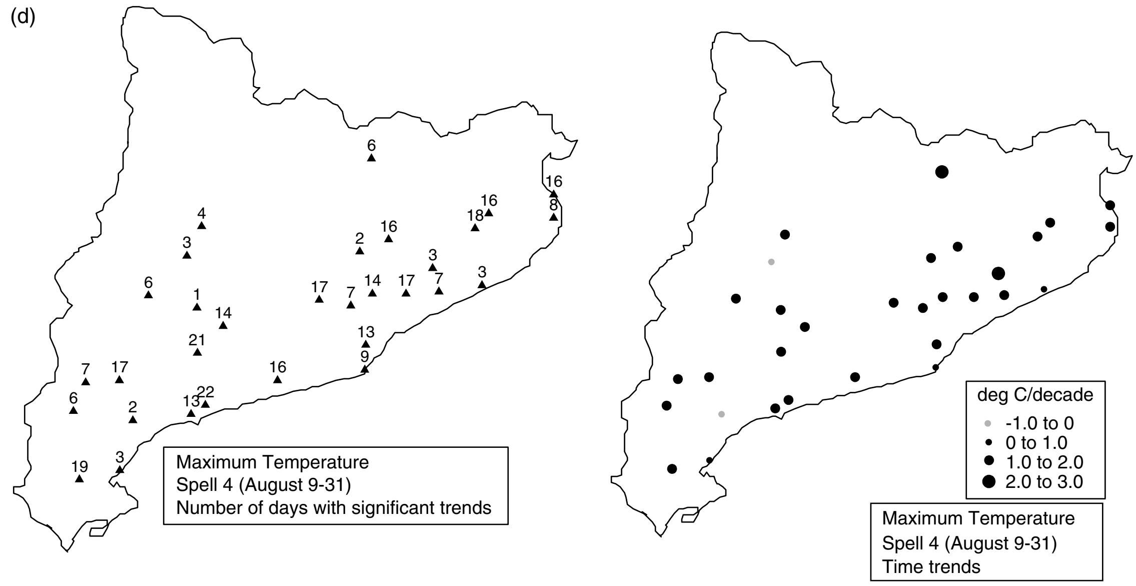

Figure 7. (*Continued*).

NAO index, the resultant effect would be coincident to a large degree (Otterman *et al*., 2002), although this oscillation keeps low correlations with the temperature in Spain in DJF months (Sáenz *et al*., 2001). The reduction in the overall cyclone activity in the Mediterranean would also aid in the warming in Catalonia, in agreement with patterns detected for daily $T_{\max}$ and $T_{\min}$ trends. As a second-order consequence, the observed northward shift of storm tracks supports more stable circulation conditions over Europe, manifested in a higher persistence of the atmospheric circulation in last decades, with the consequent exacerbation of impacts on the occurrence and severity of temperature extremes (Kyselý and Domonkos, 2006; Kyselý, 2007).

5.2. Comparisons with large-scale temperature trends

Since about 1975 up to 2004, the annual combined land surface air and sea surface temperature has increased about 0.5 °C in the world. For latitudes larger than 20°N, the increase has been close to 0.8 °C (Kennedy *et al*., 2006). This is the largest temperature increase in a 30-year period since measurements are available. In Europe, the observed increases along 1979–2005 range from −0.1 to +0.9 °C/decade, from the Iberian Peninsula to Scandinavia (Trenberth *et al*., 2007). The increase in annual $T_{\max}$ and $T_{\min}$ in Catalonia, derived from the present research, is close to 0.5 °C/decade. Consequently, the main patterns of time trends deduced for Catalonia are in agreement with those derived at global, hemispheric and European scales.

Attention has to be paid to these high temperature trends in just 30 years. As a reference, over the last 420 000 years, the highest rate has been about 1 °C/century (Salinger, 2005). Then, if the present temperature trends keep their value along this century, such as different climatic models suggest for Europe (Räisänen *et al*., 2004; Sánchez *et al*., 2004; Kjellström, 2004), the temperature change would be certainly dangerous to living organisms (Salinger, 2005).

Evidently, DTR responds strongly to forcing from soil moisture and clouds (Dai *et al*., 1999; Stone and Weaver, 2002, 2003), in such a way that it is a possible index of radiative forced climate change providing information independent of global mean temperature (Braganza *et al*., 2004). Dry soil conditions contribute to the amplification of the local temperature anomalies (Ferranti and Viterbo, 2006; Vautard *et al*., 2007). A good example could be the anomalous European hot summer of 2003, with effects enhanced by low soil moisture.

Recent studies of the twentieth century cloud cover for the two longest daily series in Catalonia shows that, in the 1975–2004 period, the cloud cover in Fabra Observatory (station 77) has an almost null linear trend and in the Tortosa Observatory (station 75) it is slightly positive (Sánchez-Lorenzo *et al*., 2006). Different time behavior is observed in a close Mediterranean domain as Italy. The cloud cover average trend is about −0.07 octa/decade in the period 1975–2004 (Toreti and Desiato, 2008), while annual temperature ATTs are similar to those deduced here. In a planetary scale, the global average trend of total cloud cover over land, years 1971–1996, is small (−0.7%/decade), offsetting the small positive trend found for the ocean, and resulting in a nonsignificant trend for the land–ocean average (Warren *et al*., 2007).

5.3. Comparisons with regional scale temperature trends

As mentioned, the temperature trends obtained for Catalonia are mainly in agreement with those established by Trenberth *et al*. (2007) for the NE of Spain (years 1979–2005), where significant positive trends of 0.3–0.5 °C/decade at annual scale and 0.5–0.7 °C/decade in spring and summer are detected. Brunet *et al*. (2007a) also obtained a significant positive trend of 0.5 °C/decade

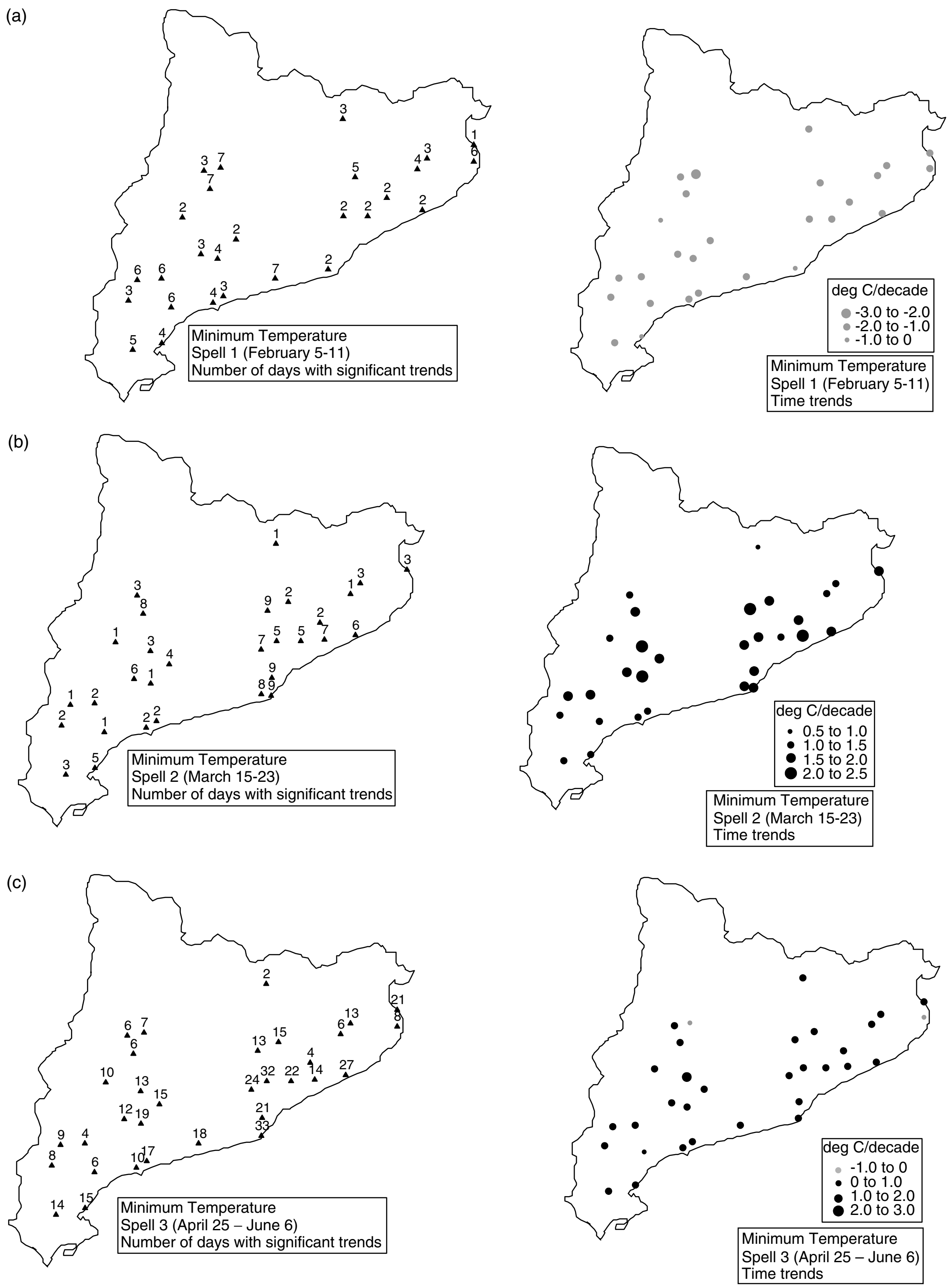

Figure 8. Number of days with significant trends and average weighted trends for the five spells of daily $T_{\min}$.

for daily $T_{\max}$, $T_{\min}$ and T_{mean} temperature over Spain at annual scale for the period 1973–2005, with spring and summer seasons mostly contributing to this warming, as deduced for Catalonia. For a region of NW Spain, Del Río *et al*. (2007) also detected positive trends of mean $T_{\max}$ and $T_{\min}$ at annual scale during the period 1961–1997, with an increase in DTR, which is in contrast with that obtained for Catalonia. Positive trends are also deduced for all seasons except for autumn ($T_{\max}$) and spring (T_{min}), but it must be mentioned that most of trends are nonsignificant. Other studies concerning temperature trends in different regions of Spain can be cited (Abaurrea *et al*., 2001; Brunet *et al*., 2001; Galán *et al*., 2001; Esteban-Parra *et al*., 2003). This warming tendency for the last 30 years is also found in other territories of the Mediterranean basin and Europe. Ben-Gai *et al*. (1999) found increasing trends of daily $T_{\max}$ and $T_{\min}$ in Israel during the warm season (years 1964–1994), together with

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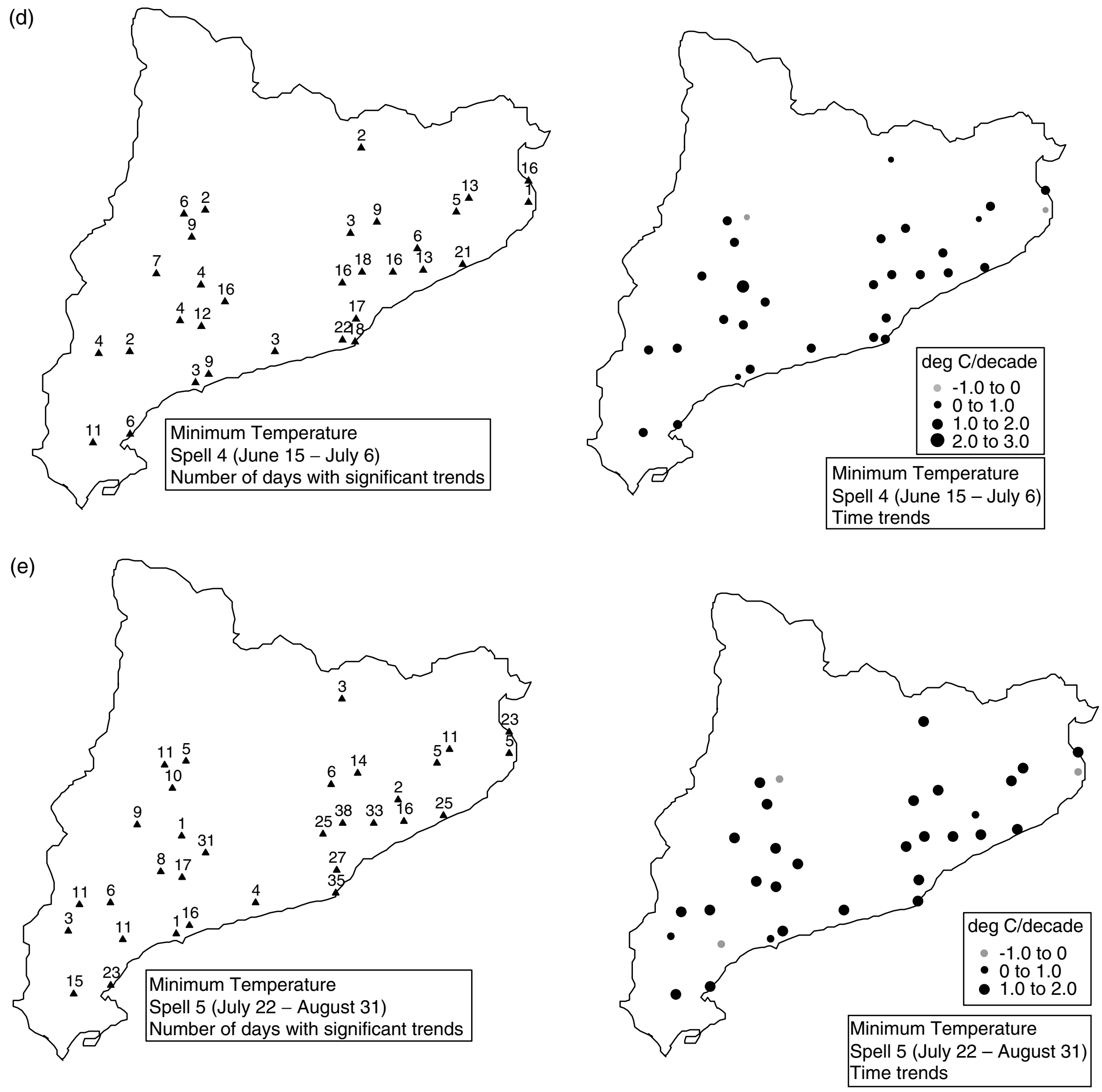

Figure 8. (*Continued*).

a decreasing of DTR, as deduced for Catalonia. Positive temperature trends, with an increase of DTR, are found in Italy for the period 1981–2004 (Toreti and Desiato, 2008). Rebetez and Reinhard (2008) found positive trends of monthly air temperature in Switzerland for the years 1975–2004, the greatest temperature increase occurring in spring and summer, as deduced for Catalonia.

The influence of the sea breeze on the smoothing effect of the vicinity to the Mediterranean coast on daily extreme temperature trends has to be briefly discussed. Sea breeze is a meso-scale coastal wind, which generates daily renewal and refreshing air in a wide fringe all along the Catalan coast in spring and summer months (Redaño *et al.*, 1991). In spite of the rapid thermal rise observed in the last 30 years, the coast and a good part of inland will continue to receive the sea breeze with similar speed characteristics than before, because the temperature gradient near the land–water boundary has remained practically constant in these last 30 years. Indeed, measures of sea surface temperature, at 2.8 km from the northern Mediterranean coast and over a bottom depth of 85 m (Figure 1b), along the 1974–2005 period, have a linear trend of 0.34 °C/decade (Vargas-Yañez *et al.*, 2005; Salat and Pascual, 2006), which is close to the measured inland trend.

6. Conclusions

The detailed analysis of daily $T_{\max}$, $T_{\min}$ and DTR in Catalonia (years 1975–2004) manifests quite evident signs of warming, which is in agreement with numerous studies focused on global warming generated mainly by an increase in the GHG effect. Two aspects of the analysis deserve to be underlined. First, the daily scale of the series permits a detailed description of the time trends along the year, notable differences among the months and seasons of the year being detected. Second, the records of all the stations permit detecting some relevant spells along the year. Nevertheless, it has to be remembered that spell lengths and ATTs are different for every station. It should be then assumed that global warming would be manifested heterogeneously at daily

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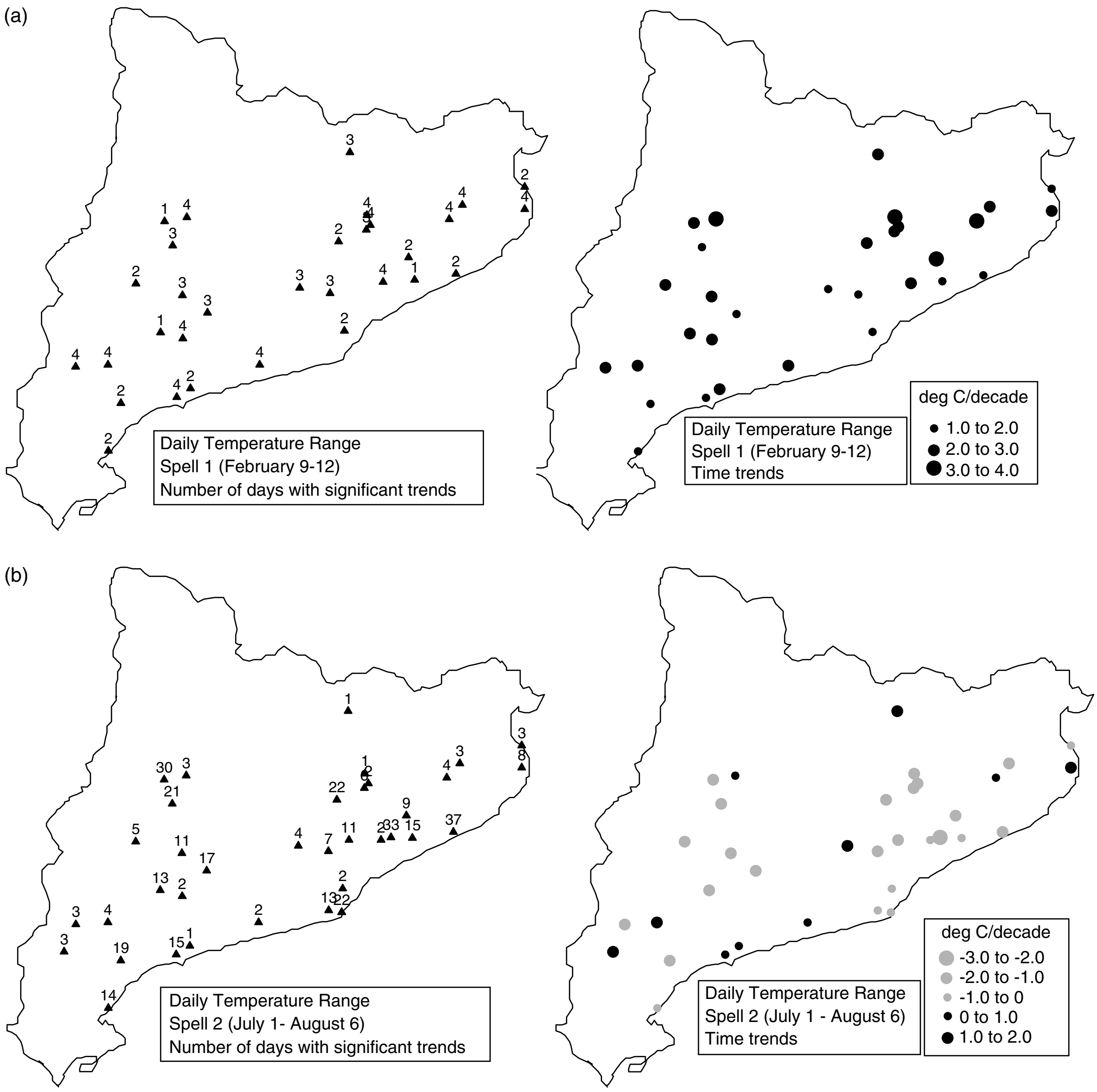

Figure 9. Number of days with significant trends and average weighted trends for the two spells of DTR.

and local scales due to the orography and the vicinity to the Mediterranean Sea.

The following are the specific features:

(1) For most of series, wrong management of daily T_{max} and T_{min} data is assumed of small relevance after the detailed application of the homogeneity tests and the comparison with years corresponding to short-period natural events (volcanic eruptions). Just two temperature series are finally rejected. Given that DTR is computed as differences between daily extreme temperatures, trends on DTR could be submitted to larger errors than those on T_{max} and T_{min}, possibly due to remaining lack of homogeneity, which is difficult to remove from daily series. However, it is worth mentioning that the relevant spells with significant DTR trends are in agreement with the time evolution of T_{max} and T_{min}, DTR trends also manifesting then the effects of the climatic change.
(2) Along the year, the number of significant daily positive trends exceeds that of negative trends and several months are characterized by the lack of negative trends for T_{min}.
(3) Whereas a low number of average daily time trends for the different s are negative, positive time trends exceeding 1.5 °C/decade are quite common, especially for daily T_{max}.
(4) A uniform positive trend along the whole year must be discarded. Nevertheless, the initial and ending dates of the four T_{max} spells (positive trends) are roughly coincident with those of the T_{min} positive trend spells (Table VI). Thus, T_{max} and T_{min} spells with relevant time trends follow a quite similar calendar evolution. The most relevant feature is their notable positive trends in spring and summer.
(5) The smoothing breeze effect on temperature trends due to the vicinity to the Mediterranean Sea is especially observed for T_{max} in spring and summer.

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(6) A single short winter spell depicts negative daily T_{min} trends. However, a negative daily T_{max} trend for this short spell is not detected, thus resulting in a DTR positive trend in the same dates.

As a summary, the detailed analysis of daily T_{max}, T_{min} and DTR certifies recent changes in the temperature regime in Catalonia, linked to global warming, but with relatively complex spatiotemporal patterns, and seasonal and annual temperature trends close to that indicated by Trenberth *et al*. (2007) for northeastern Spain. In addition, it should be stressed that the behavior at seasonal scale is an average of spells detected in Figures 6, most of them shorter than one month. Consequently, Figures 6 and their associated results could be assumed as a fine structure approach to the effects of climate change on the daily temperature regime.

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